Solenoids for MuCOOL

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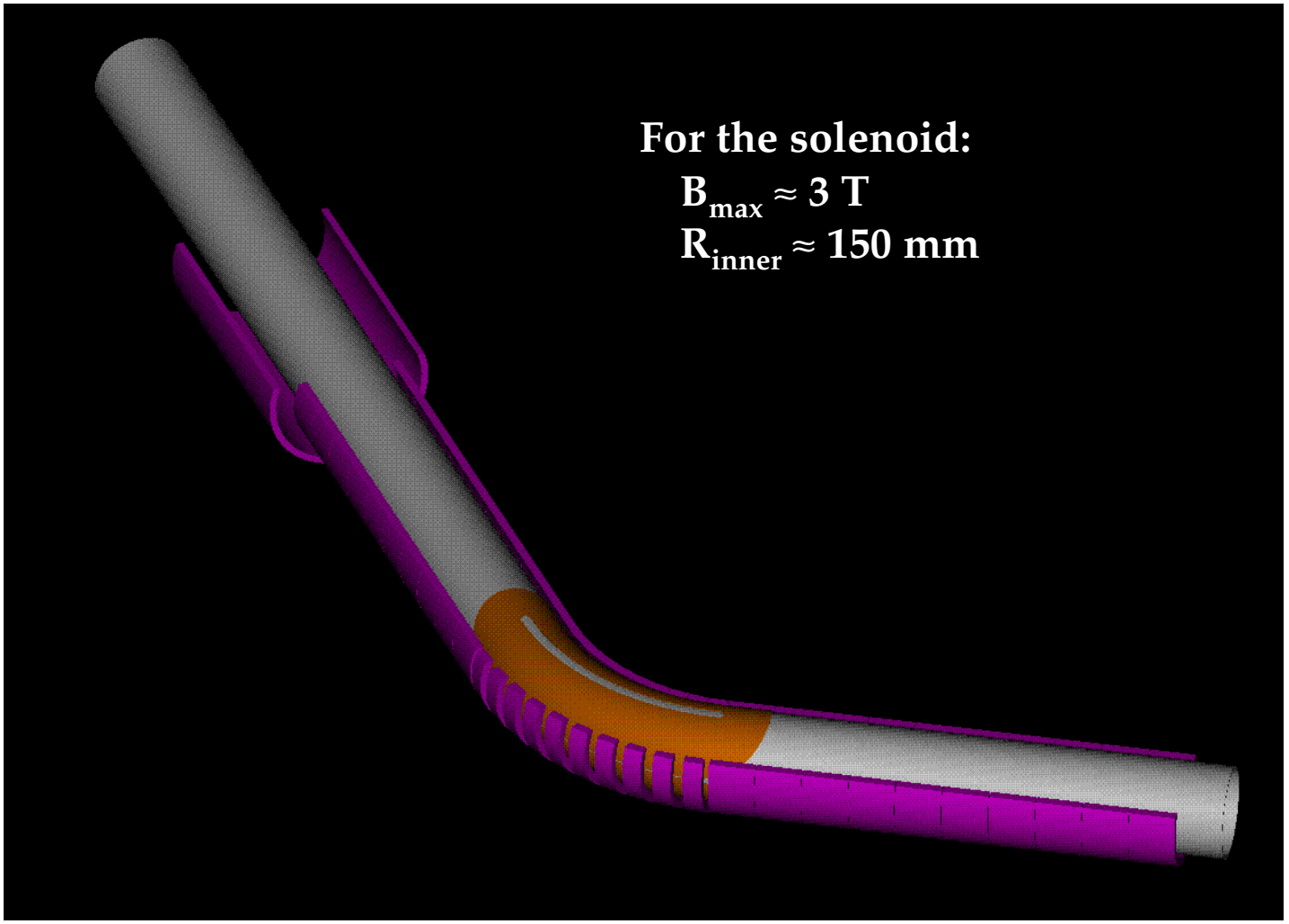
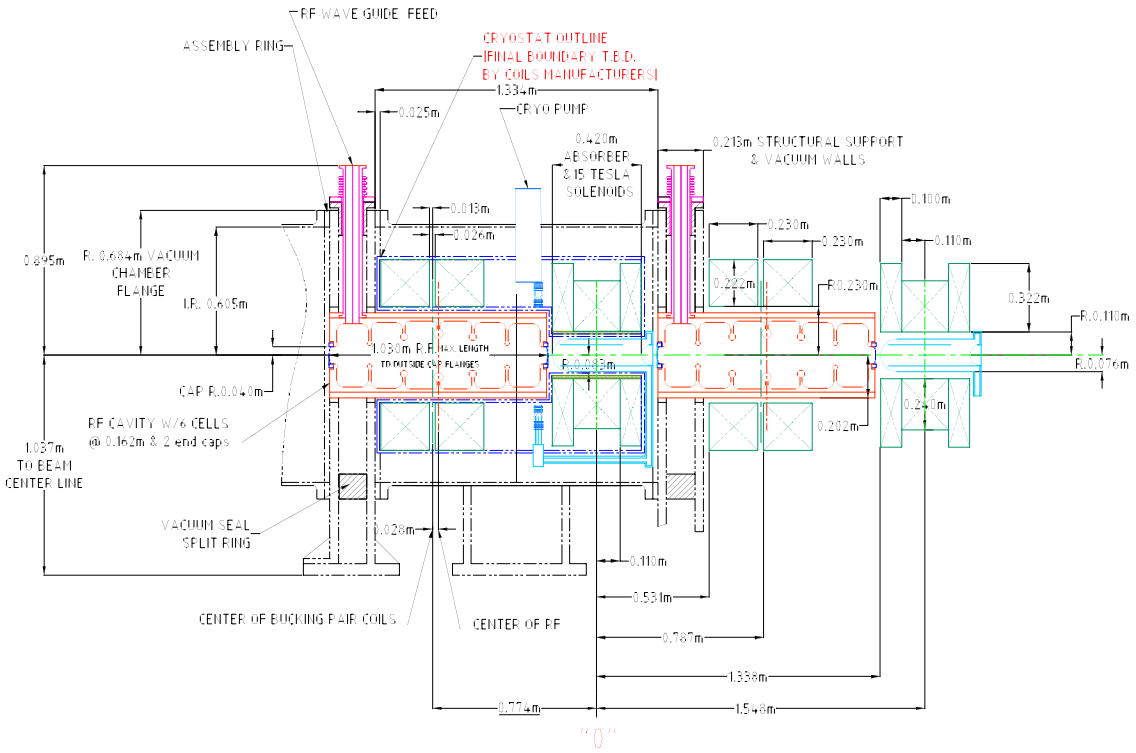
What do we need to know?

- **Designers of other subsystems primarily want to know the envelope, mass, fields, forces, etc. associated with the magnets.**
- **The overall project manager wants to know the costs.**
- **The design parameter that is most useful for helping to sort out these issues is the winding-pack current density J_{pack}.**
- **It also helps to know the composition consistent with J_{pack}.**

Bent solenoid with dipole



Alternating-Field Channel



Absorber region:

$B_{max} \approx 16.6$ T

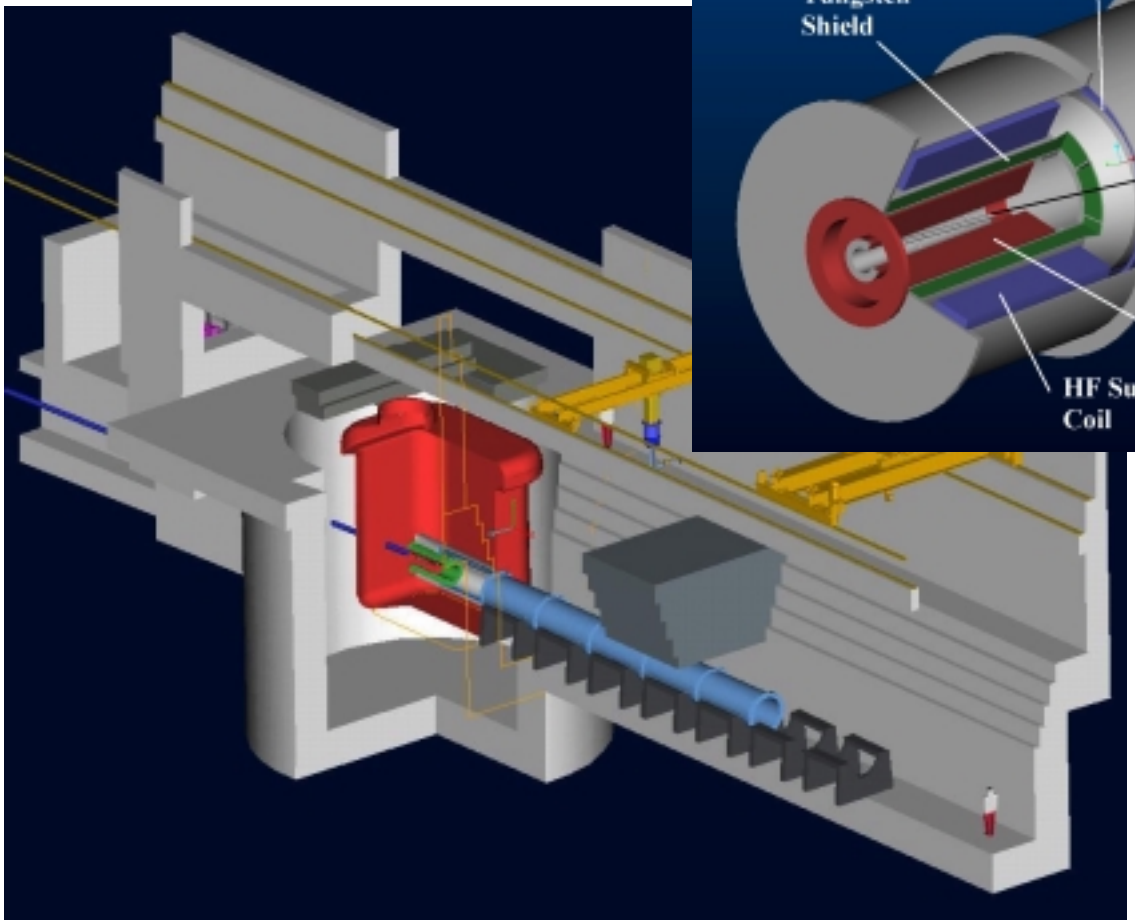
$R_{inner} \approx 100$ mm

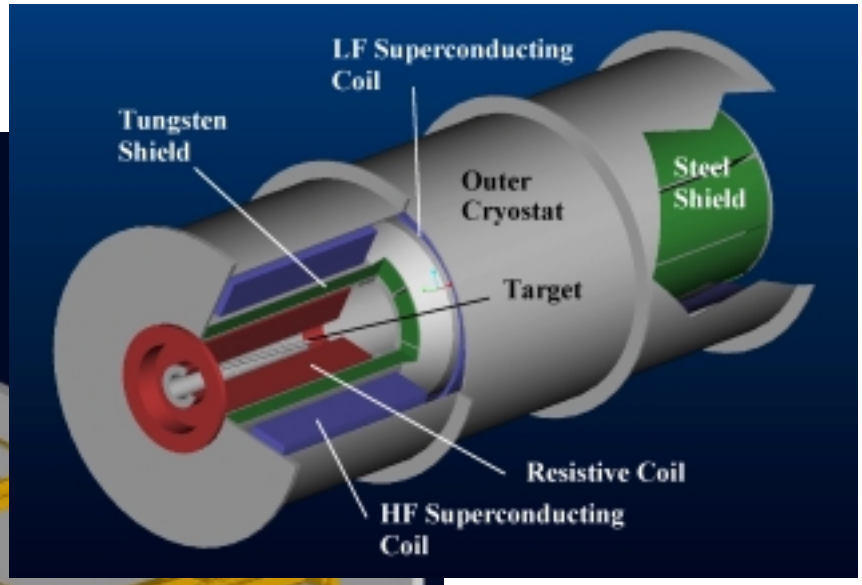
Bucking coils:

$B_{max} \approx 9.6$ T

$R_{inner} \approx 230$ mm

Target Solenoid, ν-Factory





For the High-Field Superconducting Coil:

$B_{max} \approx 9$ T

$R_{inner} \approx 500$ mm

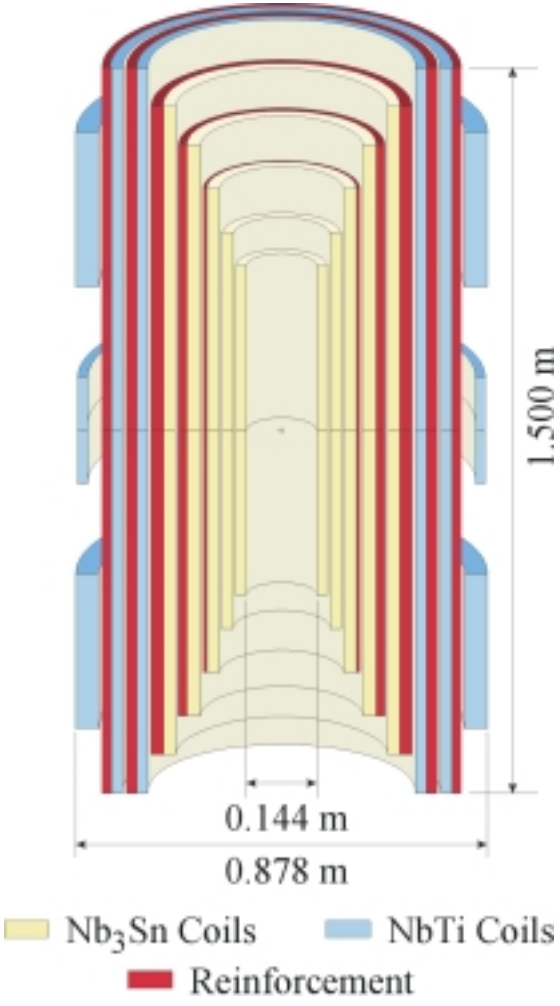
$Q'''_{rad} \sim 0.4$ mW/kg

Technologies for superconducting windings

- Impregnated windings
- Ventilated windings
  - Cryostable
  - Metastable
- Cable-in-conduit conductors (CICC)

Impregnated windings

- **Maximum J_{pack}**
- **Extremely limited stability (based on avoidance of perturbations)**
- **Rapid discharge by spreading quench**

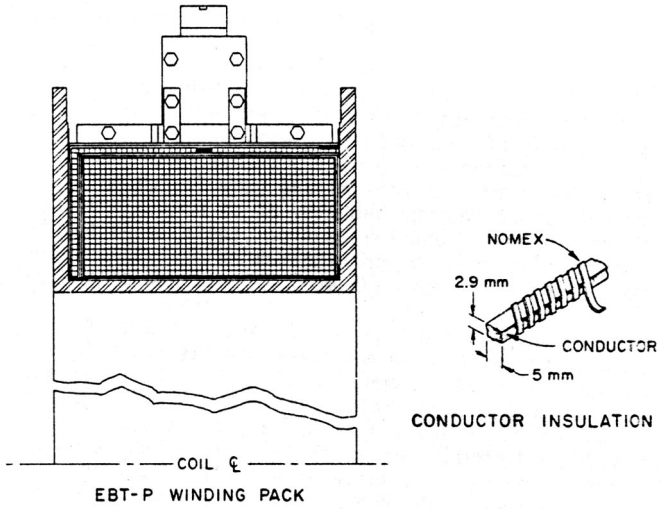


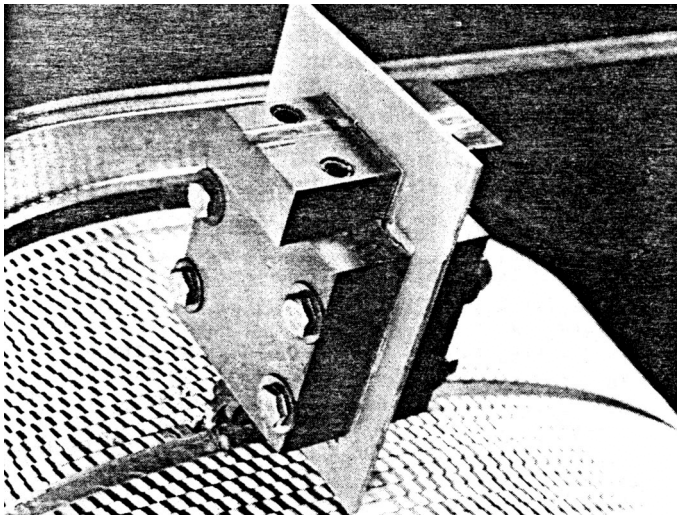
NHMFL 900 MHz NMR Spectrometer Magnet

- **$B_{max} \approx 21$ T**
- **$E_{stored} \approx 40$ MJ**
- **$35 < J_{pack} < 145$ A/mm^2**

Ventilated windings (metastable)

- **Moderate stability and heat removal**
- **Quantitative prediction difficult**





EBT-P coils*

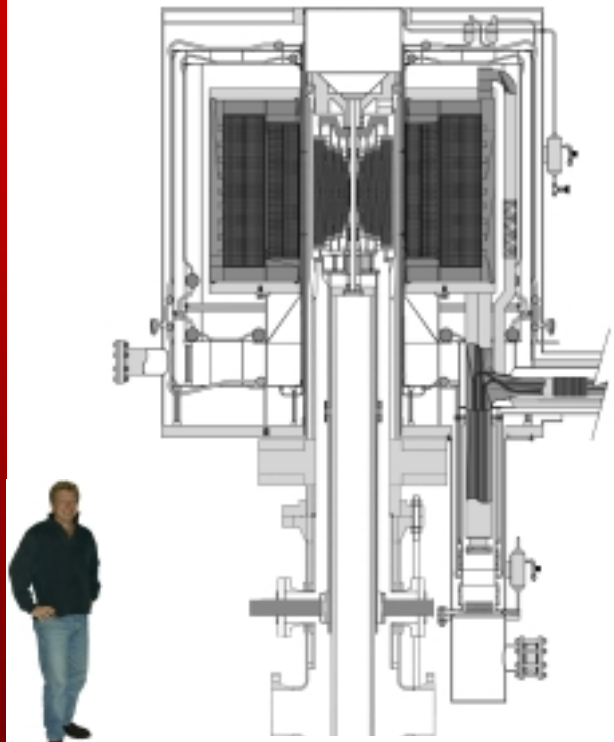
$B_{max} \approx 7.5$ T

$J_{pack} \approx 100$ A/mm^2

$E_{stored} \approx 1.5$ MJ

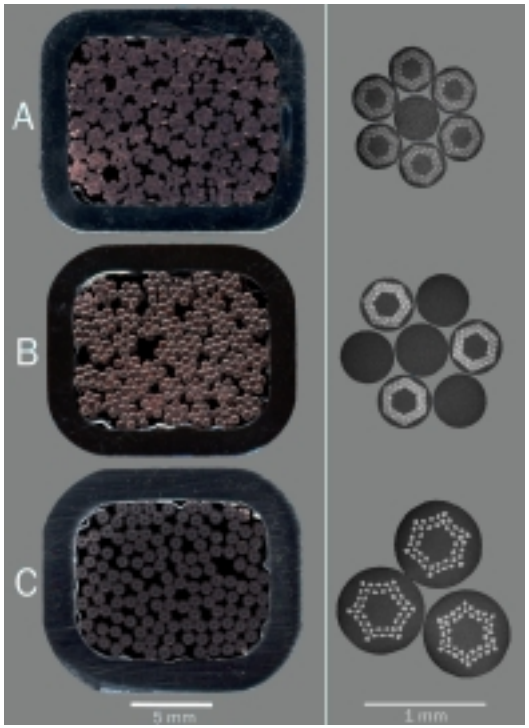
*** J.K. Ballou et al., Proc. 9th Eng. Prob. Fusion Research, p. 543, 1981**

CICC windings



NHMFL 45T Hybrid
$B_{max} \approx 16$ T
$J_{pack} \approx 40$ A/mm^2
$E_{stored} \approx 100$ MJ

- **High, predictable stability and heat removal**
- **Large conductors, applicable only to relatively large magnets**

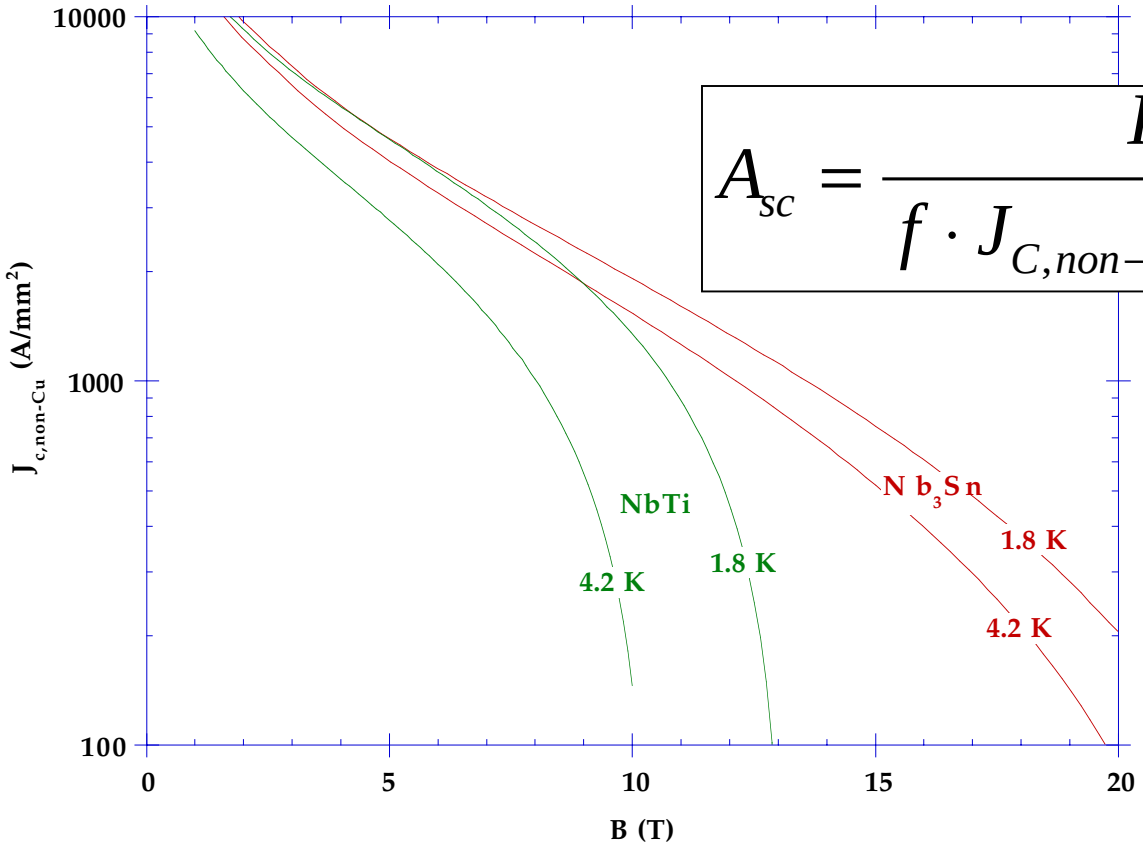


- **The essential magnet technologies appropriate to solenoid magnet systems are well understood.**
- **Issues for ν-factory solenoid design are not primarily feasibility issues.**
- **There are several issues important for reduction of cost and risk.**
- **Our approach both roots out these issues and helps prioritize them quantitatively.**

Attainable winding-pack current density

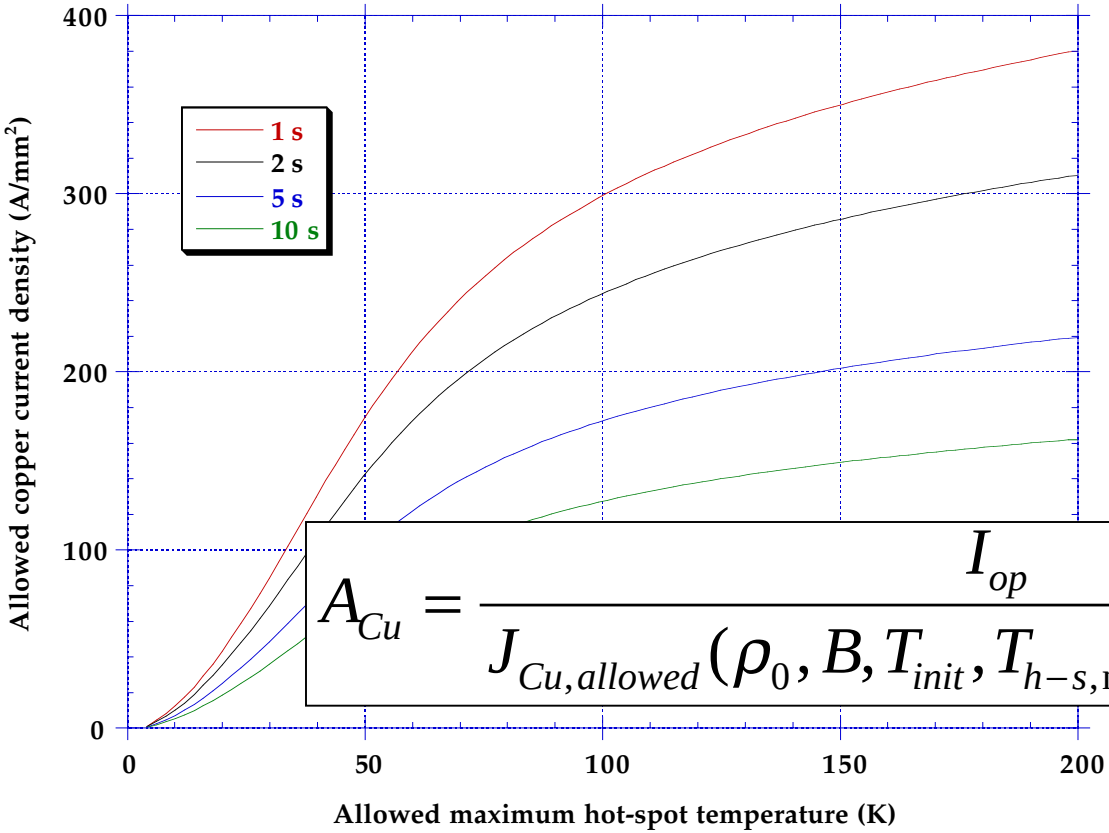
$$J_{pack} = \frac{I_{op}}{A_{sc} + A_{Cu} + A_{struc} + A_{He} + A_{insul}}$$

Superconductor cross-section



$$A_{sc} = \frac{I_{op}}{f \cdot J_{C,non-Cu}(B,T,\varepsilon)}$$

Copper cross-section for protection



$$A_{Cu} = \frac{I_{op}}{J_{Cu,allowed}(\rho_0, B, T_{init}, T_{h-s,\max}, \tau_{disch}, \Delta t_{delay})}$$

Calculated with RRR = 100, Cu/NbTi = 70/30, B = 5 T, & Δt_{delay} = 0.5 s

Structure cross-section

For solenoids,

$$A_{struc} \approx \frac{I_{op} B_{z,\max} R_{inner}}{E_{struc} \varepsilon_{hoop,allowed}} - \frac{E_{cond} A_{cond}}{E_{struc}}$$

where typically :

$E_{struc} = 210$ GPa,

$E_{cond} \sim 40$ GPa, and

$\varepsilon_{hoop,allowed} \sim 0.3\%$

Helium and insulation cross-sections

Helium in the windings provides stability and heat extraction.

Typically, $0 < \frac{A_{He}}{A_{cond}} < 0.7$

Insulation fractions typically vary with the size of conductor. For large conductors $f \sim 0.1$ but may approach 0.5 for small conductors.

$$A_{insul} = \frac{f(A_{cond} + A_{struc} + A_{He})}{(1 - f)}$$

Estimates of attainable current-densities and costs

Parameter	Bent Solenoid Channel	Alternating-Field Channel		Target Solenoid, HFSC Coils
		High-Field, Adsorber Region	Bucking Solenoids	
B_{max} [T]	3	16.6	9.6	9
T_{op} [K]	4.5	1.8	1.8	4.5
R_{inner} [mm]	150	100	230	500
Superconductor	NbTi	Nb_3Sn	NbTi	Nb_3Sn
I_{op}/I_C	0.7	0.7	0.7	0.7
Δt_{delay} [s]	0.5	0.5	0.5	0.5
$\tau_{discharge}$ [s]	1	5	5	5
$T_{hot\text{-}spot}$ [K]	150	150	150	150
A_{He}/A_{cond}	0	0.6 (0)	0.6 (0)	0.6
A_{insul}/A_{pack}	0.3	0.15	0.15	0.15
J_{pack} [A/mm^2]	200	48 (66)	65 (94)	51
System cost* [M$]	0.5	1.8		3.9

* Including magnet, cryostat, and power supply

Summary

- We understand the requirements for the various solenoid systems in the ν-factory environment.
- With very few exceptions, these systems are clearly feasible with existing technologies.
- R&D will be very useful for properly defining both the costs and risks and reducing these to acceptable levels.